

STANDARDISED MISSION OPERATIONAL METHODOLOGIES

D. ANDREWS and E. SOERENSEN

European Space Operations Centre (ESA/ESOC)
Robert-Bosch-Str. 5
64293 Darmstadt
Germany

David.Andrews@esa.int
Erik.Soerensen@esa.int

ABSTRACT

The costs of a typical Space Mission can often be subdivided roughly into three parts - 70-80% Space Segment, 10-15% Mission Control and 10-15% Data Exploitation. Economies in Space Ground Systems and Operations have been achieved throughout all types of space missions by the adoption of the appropriate standards for methodologies, interfaces and tools in all sectors, however many mission systems retain significant "one-off" elements, particularly in terms of the Space Segment design, the requirements on the mission control facilities and the operational methodologies. Such "one-off" elements act as some of the major cost drivers for the overall ground system and operations. This paper examines the application of standard design and operations concepts throughout the space mission system with emphasis on the space segment and the mission control segment. It specifically addresses the themes of fixed design menus for the space and mission control segments, the availability requirements and the maximisation of the utilisation of resources and their influence on costs.

1. INTRODUCTION

A number of significant trends in mission concepts, infrastructure development and, at least in the ESA/European context, the utilisation of existing resources are evolving such that real cost savings in mission control elements and/or systems can be achieved and which, when combined with a more standardized approach to the Space Segment design (the main cost element in the overall system) lead to significant economies in end-to-end mission costs. These trends are:

- a) Historically within ESA, space programmes have been characterized by similar (or practically identical) space segments in the telecommunications and meteorology fields e.g. the series of Marecs, ECS and MOP satellites, whereas typically Science Programmes (ESA's main non-manned space activity) have been characterized by "one-off" design. Recently, the concept of "families of missions" with similar or identical space segment sub-system (or system) designs within each family has grown in importance. Examples are:

Deep Space: Rosetta – Mars Express – Venus Express – Bepi Colombo

Observatory: (ISO - XMM -Integral) - Herschel/Planck - Eddington - Gaia

For Earth Observation missions, the concept of re-utilisation of a standard platform for the initial missions of ERS-1, ERS-2 and Envisat will be extended as far as possible to the future set of missions

Cryosat – GOCE – Aeolus – (TerraSAR-L).

Similarity of design within mission families in the key space segment subsystems such as AOCS, DHS and OBC is the main driver for economies in the mission segment of the overall programme and this can be extended to offer a menu of satellite designs tailored to complexity e.g. high, medium, low leading to different mission control implementations based upon re-use of standard sub-systems or module elements and applicable to all types of mission.

Independent of the space segment design, ground segment infrastructure as used for ESA missions has evolved considerably in the last 3 – 4 years such that the basic building blocks in many key areas have been used extensively and many times across different types of mission leading to practically complete validation at the module/sub-system level and a very stable starting point for development or tailoring for a new mission control segment. Examples of this stability in traditionally cost-heavy engineering areas are:

Mission control system:	SCOS-2000
Flight Dynamics	ORATOS
Satellite simulators	SIMSAT
Operations Engineering	MOIS
Ground Stations	TM, TC, Ranging, Station Computers, NCTRS

For identical space segment designs, development costs are basically zero given the above building blocks. For similar designs, where the basic building blocks can be re-used without significant modification e.g. at the less than 20% level, development is minimized and in both cases the effort for integration, testing at system level and validation is considerably reduced. For new developments, these validated building blocks provide the optimum starting point leading to maximum economies in the overall mission costs.

b) For many of ESA's upcoming missions in the Science and Earth Observation areas, a number of technical developments indicate a profound shift in the operational concepts, which should significantly reduce costs for the mission control development and operations, namely:

- Increase in on-board storage capability
- Increase in down –link capability with reduced contact requirements
- increase in autonomy in both space and ground segments.

These developments would lead to operations concepts, which require less access to the satellite, have a reduced dependency on ground station location and allow the possibility of more off-line operations. Exceptions to this would, of course, be any critical mission phase such as the LEOP.

Related to the above trends and coupled with the implementation of the requisite autonomy in the design of the space segment and the provision of the equivalent tools and processes in the mission control segment, an operational methodology is proposed based upon an availability requirement matrix as a function of mission phase. Specifically, it could be proposed that mission requirements can be in general satisfied with an availability index which varies from 100% during the LEOP and critical mission phases, through 98 % in the commissioning and validation phases to say 95 to 90% in the routine phase and less in any mission extension phase.

c) The facilities provided to support a particular Space Mission and the aggregate of all the facilities available at a typical Mission Control Centre for the overall programme of activities are in general not utilised to the 100% level. Coupled with the progress on interoperability and the principle of availability of spare capacity in other Networks and Control Centres, a pool of unused capacity should be readily available given adequate seamlessness of interfacing and flexibility of scheduling. This can be exploited to reduce costs for a specific mission and also to achieve a general reduction in the cost of maintaining and operating infrastructure, such as in relation to the European Public facilities with the Network of Centres initiative and within ESA the provision of Flight Operations Services to external commercial and institutional customers.

This paper addresses ESA's actual experience in relation to these themes, based upon achieved mission design costs and proposed Cost to Completion (CtC's) for future missions and gives indicative figures for potentially achievable economies in the mission control segment of typical non-manned space missions.

2. DESIGN STANDARDISATION

Standardisation covers a wide spectrum of degree of design equivalence from identical system design (eg. ESA ERS-1 and ERS-2 missions), to identical sub-system design, similar sub-system design to identical module level design and similar module level design. Each of these levels of equivalence in the design has different implications on the functional phases of a ground segment programme in support of a mission, namely: the Design and Development Phase, the Integration, Testing and Validation Phase and the Operations Phase.

Factors which critically influence the cost of these phases are:

- Design/development
 - Similarity of systems, sub-systems or modules
 - Sharing of physical infrastructure (Servers, Networks, Ground Stations, communications, control rooms)
 - Adherence to approved standards (eg. CCSDS)
- Integration/validation/testing

- Constancy of team personnel
- Use of same basic infrastructure
- Use of standard test tools, test plans and test procedures

- Operations
 - Combining of operations teams
 - Use of standard procedures/timelines
 - Shared facilities
 - Automation
 - Access to satellite.

ESA's experience of design standardisation for various families of missions can be summarised in the following tables (note that operations costs per se are only slightly influenced by design standardisation):

a) Identical Missions

Relative costs are shown for 3 sets of 'identical' missions taking the absolute costs of the first mission in each set as the baseline and considering the design/development and Integration/testing/validation phases as two separate activities.

Table 1: Relative Costs for Identical Missions

	ERS-1 (base)	ERS-2	MSG-1 (base)	MSG-2	METOP-1 (base)	METOP-2
Design/development	1.0	0.1	1.0	* 0.1	1.0	* 0.1
Integration/Test/Validation	1.0	0.5	1.0	* 0.5	1.0	* 0.5
Operations	1.0	0.9 to 0.5	1.0	* 0.9	1.0	* 0.9

* Note that the figures quoted for future missions are based upon proposed CtC's and the current understanding of requirements. In practice, a number of parameters may change and these relative costs should be taken as indicative only.

N.B. MSG-1/MSG-2 and METOP-1/METOP-2 are LEOP operations services.

- ERS-1 and ERS-2 in practice operated together as one mission, however, from the design viewpoint alone the operations costs are not significantly influenced.

Overall, assuming a normalised mission operations duration, identical missions lead to a factor of between circa 2 to 3 reduction in end-to-end costs from each base mission, depending on the type of mission and duration/complexity of the operations.

b) Identical/similar sub-systems design

Relative costs are shown within families of missions for the key sub-systems of Mission Control, Flight Dynamics and Spacecraft Simulator. In each family the first mission of the series represents the baseline and figures are given for design/development and Integration, Testing and Validation.

Table 2: Relative Critical Subs-system costs within Families of Missions

		Design and Development			Integration/Testing/Validation		
	Sub-system	Rosetta	Mars Exp	Venus Exp	Rosetta	Mars Exp	Venus Exp
Planetary Missions Base mission Rosetta	Mission Control	1.0	0.3	* 0.2	1.0	0.67	* 0.3
	Flight Dynamics	1.0	0.5	* 0.4	1.0	0.6	* 0.4
	Spacecraft Simulator	1.0	0.33	* 0.33	1.0	0.5	* 0.5
Observatory Missions Base mission Herschel Planck	Sub-system	Herschel/Planck		Eddington	Herschel/Planck		Eddington
	Mission Control	1.0		* 0.6	1.0		* 0.3
	Flight Dynamics	1.0		* 0.4	1.0		* 0.3
	Spacecraft Simulator	1.0		* 0.4	1.0		* 0.6
Earth Observation Missions Base mission CRYOSAT	Sub-system	CRYOSAT	GOCE	AEOLUS	CRYOSAT	GOCE	AEOLUS
	Mission Control	1.0	* 0.7	* 0.5	1.0	* 0.6	* 0.6
	Flight Dynamics	1.0	* 0.9	* 0.9	1.0	* 0.9	* 0.9
	Spacecraft Simulator	1.0	1.0	1.0	1.0	1.0	1.0

* Note that the figures quoted for future missions are based upon proposed CtC's and the current understanding of requirements. In practice, many parameters may change and these relative costs should be taken as indicative only.

N.B. Rosetta Mission Control System does not include Mission Planning Spacecraft simulators for Earth Observation missions have little synergy.

c) Identical/similar Module Level Design

As a general rule, the re-use of software modules from one application to the next results in cost saving mainly in the development and module level testing effort. Within a system, coding and module level testing is roughly 60% of total effort and re-use of existing code as a starting point gives a circa 40% saving in effort, thus leading to a circa 20% effect overall per module re-used. Obviously, these figures vary considerably from application to application however they serve as a useful guideline. Within the families of missions described and within individual missions themselves, re-use of software at the module level has become standard practice particularly in

view of the maturity and stability of the basic building blocks.

Examples of this include:

- The Cryosat Mission Control system, as the baseline for the further development of the GOCE and Aeolus systems (and later TerraSar-L) is itself a "delta" development from the basic SCOS-2000 infrastructure. By maximising the re-use of existing modules, the development and module level testing of the Cryosat Mission Control system has been completed for an effort, which is a factor 3 less than an equivalent new development. This has led to an overall cost for this sub-system, which is a factor of 2 less than a new development of a system of equivalent complexity.
- In a similar way, the Flight Dynamics sub-systems for the family of Earth Observation missions have been based upon

the developments carried out for the earlier series of polar-orbit missions, ERS-1, ERS-2 and Envisat. For Cryosat, GOCE and Aeolus, the development and module test effort required is a factor of between 5 and 10 less than that for the earlier missions, achieved by rigorous re-use of all existing software in a 'delta' design effort.

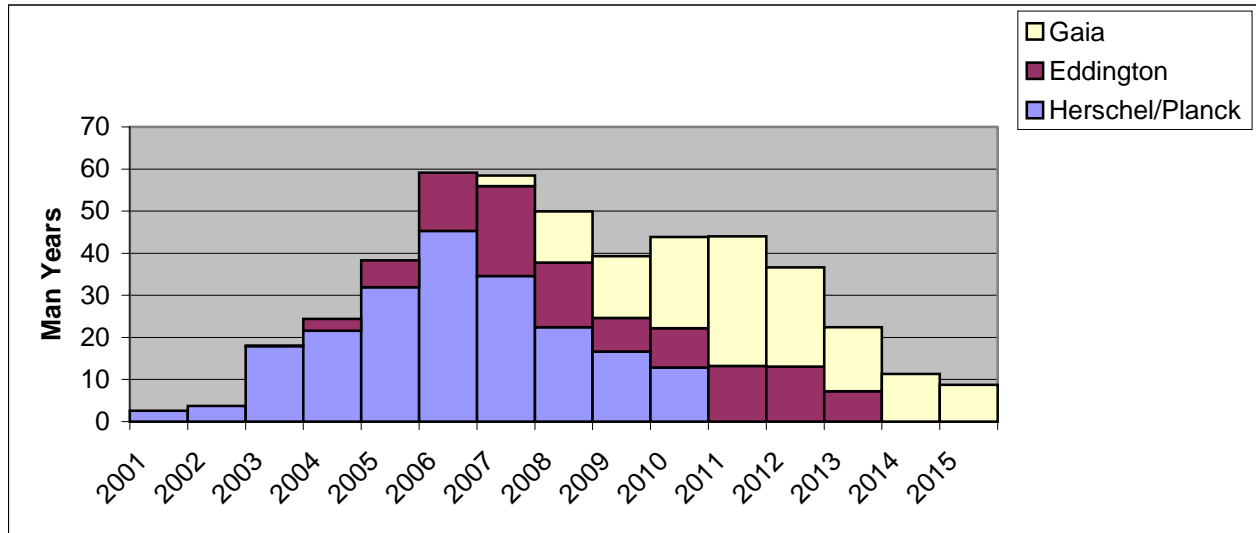
- For the SMART-1 Mission control system, only 6 % of a total of 2462 software modules in the sub-system is new, the remainder coming from a number of sources such as the basic infrastructure, and the Rosetta, Integral and MSG-1 Mission Control sub-systems. This has led to a total development effort, which is some 4 to 5 times cheaper than a new development of a system of equivalent complexity.
- The Herschel/Planck Mission Control system is a new development, which is based upon the use of the basic infrastructure, SCOS-2000, for the Satellite checkout and for Payload check-out at the P.I. Institutes and for testing throughout the satellite AIT programme. From an overall programme perspective, the use of the same infrastructure across the payload, Spacecraft and ground segment developments leads to significant project-level economies, including for example for the operations preparation the provision of a fully validated and compatible satellite reference database.

Summary and Discussion

Design standardisation in the space segment, particularly in sub-systems as DMS, OBS and AOCS, and in the ground segment using to the maximum extent possible validated basic infrastructure and existing software modules gives significant savings in the design/development and Integration, Testing and Validation phases of a ground segment development. For design and development, factors of 2 to 3 in cost reduction can be achieved at the module and sub-system level, leading in the extreme case to practically zero cost in this phase for identical space segments. For the Integration, Testing and Validation phase, cost savings of between 50% to 25% are achievable as a result of the design similarity but, additionally, from the re-use of the same engineering teams (staff) from one mission to the next. This is facilitated by the concept of mission families and is illustrated in Figure 1, which shows the manpower profile over 15 years for the Observatory family of ESA science missions. A fairly constant size of the combined team over a period of about 8 years, as well as being advantageous for management and staff planning, makes the learning and training processes efficient and offers considerable economies in the testing and validation activities.

ESA has over the last 5 years made steady progress towards design standardisation and we will be discussing with our partners in the Science and Earth Observation directorates the evolution of this concept, towards more fixed design menus for all space segments, characterised perhaps by 'complex', 'medium' and 'simple' systems. Using the standardised infrastructure and validated software modules, standard ground segment engineering development can be proposed allowing at the same time optimum re-use of teams and procedures.

Figure 1. Observatory Family Manpower Levels



3. FUTURE TRENDS AND REQUIREMENTS ON AVAILABILITY

In the previous section, the re-use of facilities and personnel has been examined in respect of ground segment developments pre-launch. Similar considerations apply to the operations phase. Combining operations teams, sharing of facilities (control rooms, ground stations, communications infrastructure) and automation are all integral components of the assessment of operations concepts for current ground segment design.

In addition, there are major savings that could be achieved from the Space Segment design, where two main elements significantly impact the operations costs, namely:

- The satellite-ground contact frequency and duration

- The requirements for telemetry data recovery.

The contact frequency and duration influence significantly ground segment and operations costs and a spacecraft design allowing for fewer and shorter contact periods would decrease operations costs. In addition if the spacecraft design provides for flexibility in the contact time, normal working day operations could become the baseline operations concept.

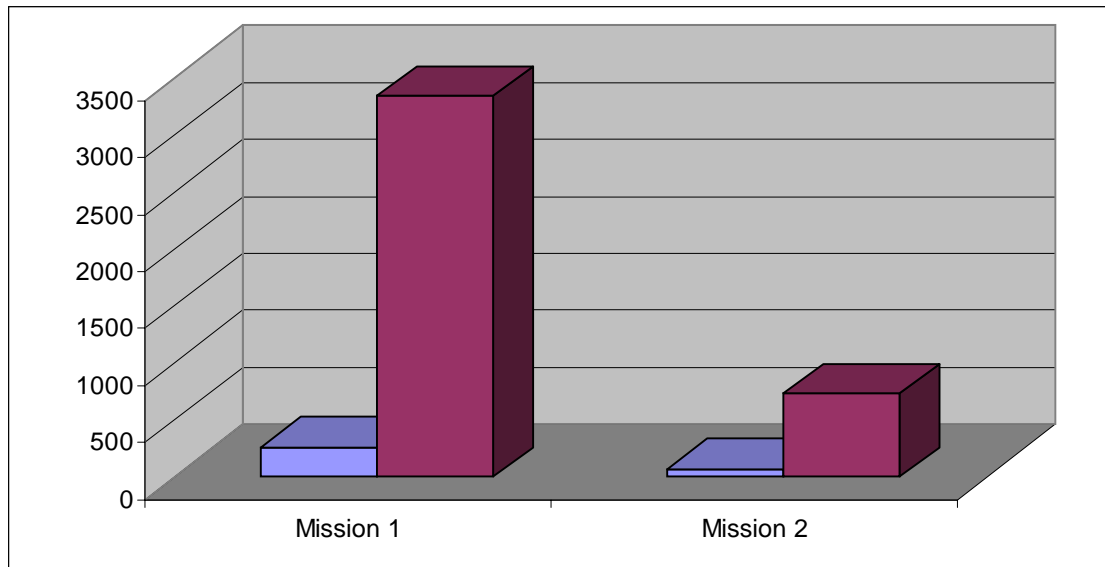
The requirement for telemetry recovery is a major cost factor. There are some missions that need permanent ground contact and 24 hr per day manning of the mission control centre. Such a system design drives the cost and requires more quality and redundancy in the ground system design. This can be illustrated with the following comparison between two missions.

	Mission 1	Mission 2
Contact Frequency and Duration	Full coverage requiring 3 stations around the globe and each used 8 hours per day.	One contact every 3 rd day using one ground station for 8 hours.
Mission Control Staff	Full support of one person 24/7 requiring in total 12 people to cover such a support	Only support during normal working hours and no support during weekends. This requires a maximum of 3 people to cover such a support

ESOC's experience shows (Fig. 2) that two such missions have the following relative costs (blue

for the pre-mission training and red for the operations costs):

Figure 2. Relative costs of Missions



Pre-mission training costs for mission 2 are about 25% of those of mission 1 and the running costs are about 22 % of mission 1. This illustrates very clearly that reducing the contact time and frequency of contact and the number of staff needed for Mission Control will significantly lower the cost. The above example suggests a saving of up to 75%.

To achieve this, the design of the space segment must be addressed, particularly in three key areas:

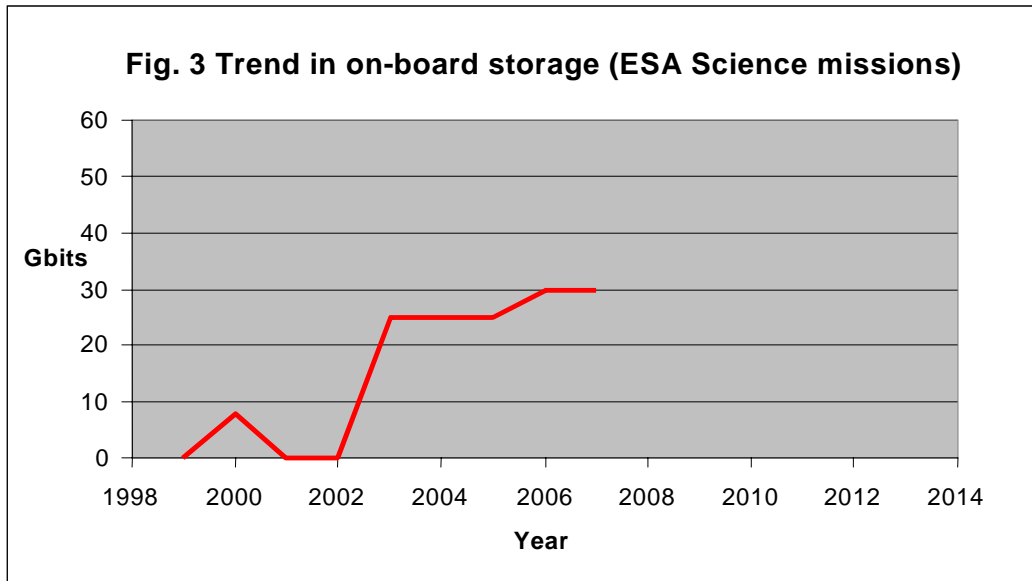
- On-Board autonomy
- On-board storage
- Downlink rate.

On-Board Autonomy

When a spacecraft is able to operate without direct support from the ground, it has on-board autonomy. It should be one of the prime objectives of the system engineering to design and develop a spacecraft that requires minimal operations support. In the past, system engineering at the space segment level has often led to 'less on-board' and 'more on ground', however, a more system-oriented approach with on-board autonomy would give a design requiring less operations support.

On-Board storage

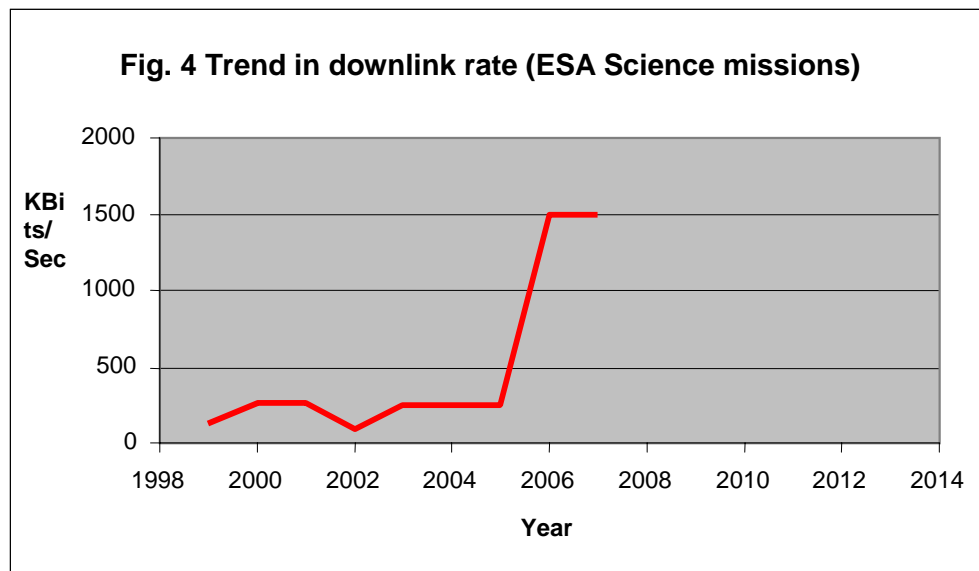
When a spacecraft is not in direct contact with the ground, data must be stored on-board. Today most satellites are using a Solid Mass Memory for storing data, which provides flexibility in storing and retrieving data. Figure 3 shows the trend in the size of the on-board storage for the current ESA science missions.



There is a continuing evolution in the on-board storage capability and currently planned missions foresee up to 30 Gbits of storage.

Downlink rate

To reduce the contact time with the spacecraft and to be able to dump the on-board storage, a higher downlink rate is required. Figure 4 illustrates the current trend in downlink capability for the ESA science missions.



The combination of these three elements will make it possible to reduce the ground-space contact time and size of the mission operations team. The result is a major cost saving for the operational phase of the mission.

Summary and Discussion

There are a number of trends which can be observed and which are evolving as shown below:

Trend	Reason
Increased autonomy	To allow for the satellite to operate with minimum ground intervention
Increased downlink	To lower the contact time and to be able to dump the on-board storage
Increased on-board storage	To store data during non-contact period
Increased confidence	The grouping of missions and in particular the re-use of the same on-board, ground systems, and the fact that the same team can operate multiple missions will increase the confidence in the spacecraft design and the operational teams
Increased demand to save cost	There is a continuous pressure to reduce the cost
Increased acceptance of risks	This follows with the increased confidence. With an increased confidence and the increased autonomy a higher risk on the ground segment and in operations. In case of problems we will be safe but mission products might be unavailable

It is clear that the demands to save cost, the acceptance of risks and in particular the increased confidence supported by the evolution in on-board technology may spearhead an evolution towards off-line operations. Off-line operations in this context shall be understood that the time of contact between the spacecraft and the ground station is independent of the contact time between the ground station and the mission control system. A typical scenario would be that the mission control team during working hours will prepare the commands to be uploaded to the spacecraft for the next pass during normal working hours and download them to the relevant ground station. The ground station will then subsequently uplink the command during the next satellite pass. Similarly, telemetry will only be down linked to the ground station during the pass and retrieved from the mission control centre during working hours.

4. OPTIMAL UTILISATION OF INFRASTRUCTURE

ESA maintains a global Network of ground stations, offering S-, X- and Ka- band capabilities, and the associated communications network together with, at ESOC in Darmstadt, a Network Management Centre and a number of common and dedicated mission control facilities. The maintenance of this infrastructure, which has been established in response to the requirements of the ESA programmes, is a significant element in the overall Ground Segment costs for individual projects and collectively. This is recovered partially from the users of the facilities (the ESA projects) and partially from Corporate funding. Generally, a utilisation factor of 70 to 80% for any facility is an achievable goal, given a

If it would be possible to design a mission to allow for off-line operations during the routine phase this would offer a number of potential areas for cost savings. One of the major cost savings is in the manning, as permanent manning would not longer be required. Another important consideration is the use of ground stations. Because the spacecraft have on-board autonomy and large on-board storage, the ground contact patterns would allow for more flexibility. This basically means that the ground stations could be located anywhere with the requirement to simply have regular contact opportunities. For an organisation operating a number of ground stations around the globe an optimisation of an overall network by grouping antennas at single locations and selecting favourable places in terms of running costs, access and maintenance etc. is possible.

sufficiently large, varied and sustained programme of missions. It is, however, difficult to achieve such load factors except for relatively short periods and significant periods of non- or minimum utilisation often occur. An extreme solution is to close any facility, which is unused over the foreseeable future, but such a decision is often strategically complex and politically difficult. Normally, such periods of non-optimal utilisation of facilities must be covered by existing budgets and it is clearly important to find ways to absorb as much as possible spare capacity in the existing infrastructure.

ESOC currently offers its spare capacity in Flight Operations, both expertise (personnel) and facilities, to external (non-ESA) customers on a commercial basis and without interference with

ESA's own programmes. An External Services Office has been established with the responsibility to promote the utilisation of ESOC's flight operations skills and facilities, to respond to Customer's enquiries and to make offers of Services to both Industrial (mainly European) and Governmental entities. Examples of such services include LEOP operations, Station or Network provision, Back-up mission control and precise orbits/clocks for GPS/ Glonass satellites.

During the previous 3 years (2000 to 2002), a volume of activity representing about 7 to 10 % of ESOC's turnover has been established with new Contracts for ESOC's services concluded with many European and International Organisations, both commercial and public. Our goal is to increase this to the 10 to 15% level to provide a solid workload within the framework set of ESA programme support and which optimises the utilisation of spare capacity in the existing facilities and reduces the cost, both at corporate level and to the users, of providing the ground infrastructure for the user programmes.

In a similar vein, an ESA council decision in 1999 led to the establishment of a pilot Network of Centres (NofC) initiative to optimise the use of European-wide infrastructure owned by the various European public agencies – ESA, ASI, BNSC, CDTI, CNES, DLR, NSC, SSC. Four themes were chosen for an initial 2- year qualification phase (2001/2002) – Flight Operations, Test Facilities, Project Reviews and Space Debris. In the Flight Operations area, the qualification phase has comprised an analysis of Station utilisation and harmonisation, Control centre utilisation, Standard systems, Concurrent

engineering and the European Deep Space Network and has established a consistent and coherent database of programmes, satellites and facilities. Within the broad goal of using existing facilities and avoiding as far as possible the creation of new facilities (except where necessary eg. Deep Space Antennas), the operational Phase of the NofC, which should start this year, will:

- Implement flight operations needs of future programmes (EU, ESA and national) through an operational Network of Flight Operations Technical Centres.
- Harmonise and rationalise necessary facilities, competencies and resources to meet the needs.
- Optimise the Flight operations technical centres for efficiency and effectiveness.

Summary and Discussion

Reducing the overall volume of ground infrastructure to be maintained and minimising the addition of new facilities together with utilising any remaining spare capacity clearly leads to cost reductions for all ground segment developments and operations. With the progress in interoperability already achieved and the standardisation of interfaces according to CCSDS (eg. SLE services), it will become easier to increase the optimal use of the available facilities.

5. CONCLUSION

Design standardisation, with similar or identical space segment sub-systems and ground segment engineering based upon re-use of validated infrastructure, operations concepts based upon increased 'off-line' operations and seamless interoperability and exploitation of the globally available ground infrastructure will define the next major economy in space mission operations. The grouping of missions into various families and the establishment of manpower teams across each family will accelerate this, increasing confidence in the operations process allowing acceptable risks to be determined and taken and leading eventually to full 'off-line' operations, except in critical mission phases. ESA itself, and in a European context, has embarked on this evolution and through dialogue with the users of its operations services will seek to implement as far as possible these concepts in future mission operations.

ACKNOWLEDGEMENT

The authors wish to acknowledge the many valuable discussions with their ESOC colleagues, particularly with Rolf Münch, Michael Jones, John Dodsworth, Nigel Head, Manfred Warhaut, Howard Nye and Pier Paolo Emanuelli.

GLOSSARY

AIT	Assembly, Integration and Test
AOCS	Attitude and Orbit Control System
CtC	Cost-to-Completion
DHS	Data Handling Sub-system
OBC	On-Board Computer
ORATOS	Orbit and Attitude Operating System
LEOP	Launch and Early Orbit Phase
MOIS	Mission Operations Information System
NCTRS	Network Command and Telemetry Routing System
PI	Principal Investigator
TC	Telecommand
TM	Telemetry